feature articles

MABEL and the ICESat-2 Mission: Photon-counting Altimetry from Air and Space

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Mission Overview

Understanding the causes and magnitudes of changes in the cryosphere[1] remains a priority for Earth science research. Over the past decade, NASA's Earth-observing satellites have documented a decrease in both the areal extent and thickness of Arctic sea ice, and an ongoing loss of grounded ice from the Greenland and Antarctic ice sheets. Understanding the pace and mechanisms of these changes requires long-term observations of ice-sheet mass, sea-ice thickness, and sea-ice extent.

NASA's Ice, Cloud, and land Elevation Satellite (ICESat) mission, which operated from 2003 to 2009, pioneered the use of laser altimeters in space to study the elevation of the Earth's surface and its changes. Among other contributions to the cryospheric sciences, ICESat proved adept at making the centimeter-level elevation measurements—required to document subtle changes in the elevation of ice sheets—that indicated an ongoing loss of ice to the ocean. Subsequent investigation revealed that the Greenland ice sheet discharges some 175 billion tons of ice—every year—into the sea, either by calving icebergs or melting at the ice-sheet surface. Similarly, ICESat sea-ice data were used to determine the thickness of sea ice in the Arctic and how that thickness distribution changed over time. These data revealed that approximately 40% of the multi-year sea ice that was lost during the ICESat observation period was replaced by much thinner and less-stable first-year sea ice. In addition, ICESat contributed to a wider range of Earth science disciplines that also require precision elevation measurements, disciplines that range from geodesy to geology, and from atmospheric science to land-use management.

As a result of ICESat's success, the National Research Council's (NRC) 2007 Earth Science Decadal Survey recommended a follow-on mission to continue the ICESat observations. In response, NASA tasked its Goddard Space Flight Center (GSFC) with developing and deploying the ICESat-2 mission—now scheduled for launch in 2016. The primary goals of the ICESat-2 mission are consistent with the NRC's directives: *to deploy a spaceborne sensor to collect altimetry data of the Earth's surface optimized to measure ice sheet elevation change and sea ice thickness, while also generating an estimate of global vegetation biomass*. As a result of this direction, the ICESat-2 science definition team developed the following four science objectives:

- Quantify polar ice-sheet contributions to current and recent sea-level change and the linkages to climate conditions.
- Quantify regional signatures of ice-sheet changes to assess the mechanisms driving those changes and improve predictive ice sheet models; this includes quantifying the regional evolution of ice sheet change, such as how changes at outlet glacier termini propagate inward.

[1] Cryospheric research at NASA addresses the physics of ice sheets and glaciers, sea ice, snow on ice and land, and their roles in the global climate system.

- Estimate sea-ice thickness from *freeboard*[2] measurements to examine ice–ocean–atmosphere exchanges of energy, mass, and moisture.
- Measure vegetation canopy height as a basis for estimating large-scale biomass and biomass change.

These objectives subsequently lead to eight primary science requirements related to monitoring ice sheet elevation change, on scales ranging from that of outlet glaciers [100 km^2 (~38.6 mi^2)] to the entire ice sheet [10^6 km^2 (~386,102 mi^2)], measuring sea ice thickness change, and generating an independent estimate of the global vegetation biomass. In particular, ICESat-2 has a requirement to produce an ice-surface elevation product that enables determination of whole ice-sheet elevation changes to an accuracy of 0.4 cm/yr (~0.16 in/yr) on an annual basis. This is a demanding requirement that drives pointing knowledge, measurement signal-to-noise ratio, and orbital considerations.

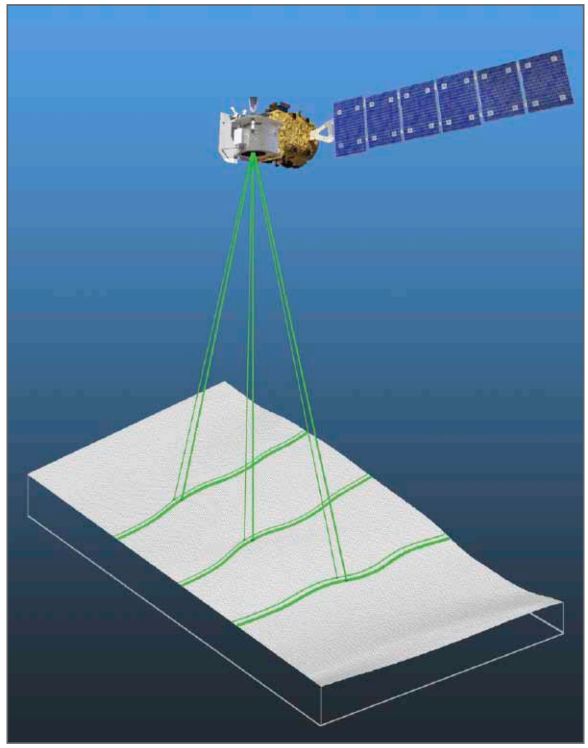

Figure 1. Schematic drawing of the six beams of ICESat-2—an advancement over ICESat, which had only one beam. **Image Credit:** ICESat-2 Mission.

Mission Design

In developing the mission concept for ICESat-2, GSFC and the science definition team sought to correct some of the limitations that arose in ICESat's design and on-orbit performance. ICESat was launched into a 94° inclination orbit that collected data between 86° N and S latitudes. The altimeter on ICESat—the Geoscience Laser Altimeter System (GLAS)—operated in the infrared at 40 Hz and used an analog detection system to record reflected laser energy by digitizing a waveform. This approach led to discrete *footprints*, with a nominal 70-m (~230-ft) diameter spot spaced every 170 m (~558 ft) in the direction of flight. Operationally, ICESat was designed to run continually for three to five years, although unforeseen manufacturing defects caused a substantial reduction in the laser's planned lifetime. Instead, ICESat subsequently operated in *campaign mode*, conducting 18 discrete 33-day campaigns over the seven years ICESat was on orbit.

While retaining many of the same measurement objectives, ICESat-2 differs in design from ICESat in several important ways.

The current design for ICESat-2 makes use of a more-rapid laser repetition rate (10 kHz, in contrast to the original 40 Hz); it also uses low pulse energy on the transmitter side and sensitive single-photon detectors on the receiver side to measure the range to the Earth using green light at 532 nm. This detection strategy allows ICESat-2 to use lower-energy laser pulses than the waveform-digitization strategy of ICESat. The mission planners have elected to use a much smaller footprint of 10 m (~33 ft)—compared with the 70 m (~230 ft) of ICESat—to limit the impact of surface slope and roughness that reduce the precision of each measurement. The high repetition rate causes overlap between each successive footprint, as the along-track spacing of the footprints is ~70 cm (~27.6 in). The orbit for ICESat-2 is both lower—500 km (~310 mi), compared with 600 km (~373 mi) for ICESat—and has a lower inclination angle of 92°, leading to coverage between 88° N and S latitude. Perhaps most

[2] Sea ice floats in the ocean, as an ice cube floats in a glass of water. Due to the differences in the density of water and ice, about 10% of the thickness of the ice floats above the waterline. The difference in height between the top of the ice and the waterline is called the *freeboard*. The news article on page 48 of this issue discusses freeboard in more detail, as well as other topics mentioned in this article.

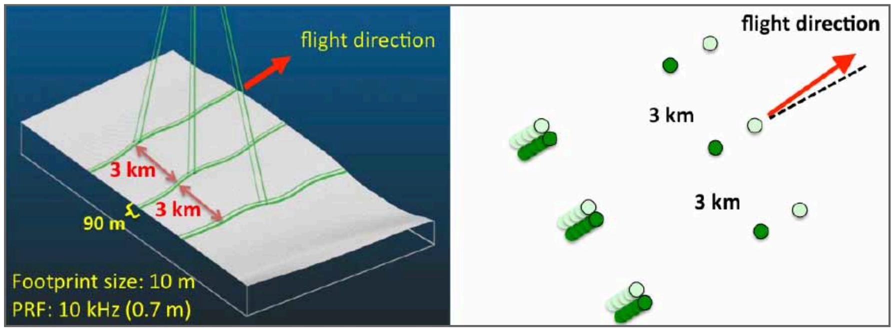

Figure 2. Details of the ICESat-2 measurement concept. Each laser pulse is split into six beams, arranged into three pairs. The ~3-km (~2-mi) separation of the beam pairs improves spatial coverage, while the ~90-m (~295-ft) spacing within the pairs allows measurement of the surface slope.

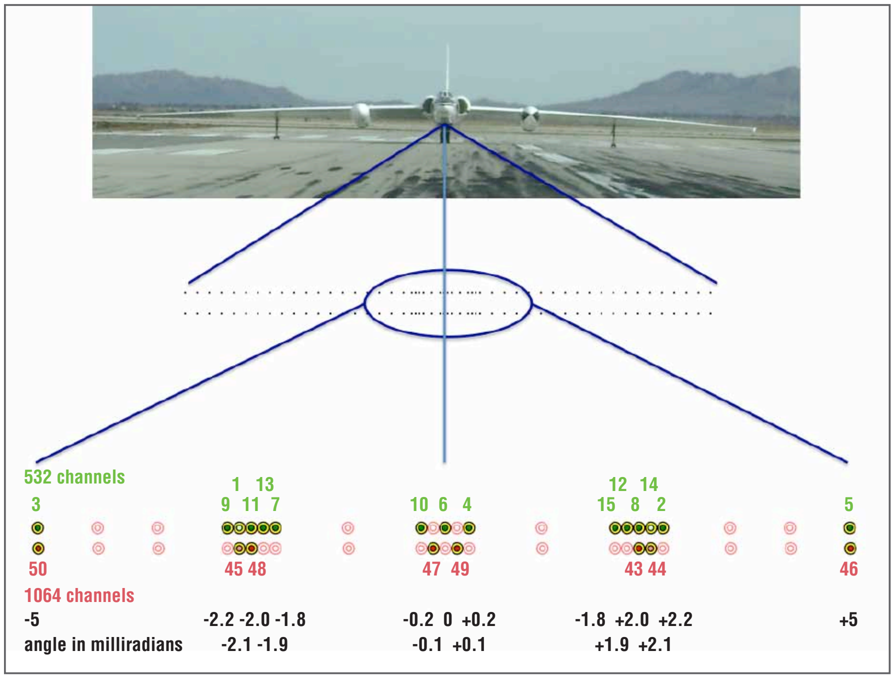

Figure 3. MABEL has 105 different channels available in either the green (532-nm) or infrared (1064-nm) parts of the spectrum. Users can select up to 16 green channels and 8 infrared channels to use for a specific flight. The lower half of the figure shows a configuration where the channels nearest to *nadir* have been illuminated, providing dense sampling directly beneath the aircraft; the angles of each channel are provided in milliradians.

importantly, ICESat-2 splits each laser pulse into six separate beams, arranged in pairs of three. The ~3-km (~1.9-mi) separation between beam pairs substantially improves the spatial coverage over the single beam of ICESat, while the 90-m (~295-ft) spacing of beams within a pair allows measurement of the surface slope—**Figures 1** and **2** illustrate the ICESat-2 measurement concept.

MABEL: The Airborne ICESat-2 Simulator

Given the substantially different design of ICESat-2 as compared with ICESat, the ICESat-2 project elected to develop an airborne simulator to generate ICESat-2-like data for algorithm development, and to verify ICESat-2 instrument models over the very cryospheric targets that are the science focus of the mission. The Multiple Altimeter Beam Experimental Lidar (MABEL) is not an exact copy of the ICESat-2 instrument, but it has enough similarity to allow MABEL data to be scaled to space-like geometry and radiometry, and includes additional flexibility to explore the capabilities of ICESat-2.

Like ICESat-2, MABEL uses a high-repetition-rate, low-power laser transmitter mated to a sensitive single-photon detection system. To compare the differences between altimetry measurements made with green light (such as used in ICESat-2) and those made with infrared light (such as used in ICESat), MABEL makes concurrent measurements at both frequencies. To better understand how to effectively use and combine information from multiple beams, MABEL is configured to simultaneously use up to 16 channels in the green part of the visible spectrum, and eight additional channels in the infrared. While the angles of ICESat's six beams are fixed with respect to each other, MABEL uses what is essentially a telephone-switchboard design to allow users to choose from 105 different channels in the green, and another

105 different channels in the infrared. Prior to a flight, users select which channels are to be illuminated, and connect fiber optic cables to the appropriate channels as desired. The maximum view angle for MABEL is ±3°, or just over ~1 km (~3281 ft) across the direction of flight. A schematic of the channels available on MABEL is shown in **Figure 3**.

To sample as much of the atmosphere as possible, MABEL operates at an altitude of 20 km (~12 mi) aboard NASA's ER-2 aircraft, operated out of NASA's Dryden Aircraft Operations Facility, which is inside Edwards Air Force Base, in California. This single-pilot, zero-passenger aircraft has long been used as a means to fly as close to space as possible, yet still permit researchers to adjust instruments and analyze data between flights. A small stream of housekeeping data is downlinked in real time, but science instruments aboard the ER-2 operate autonomously, much like a spaceborne instrument.

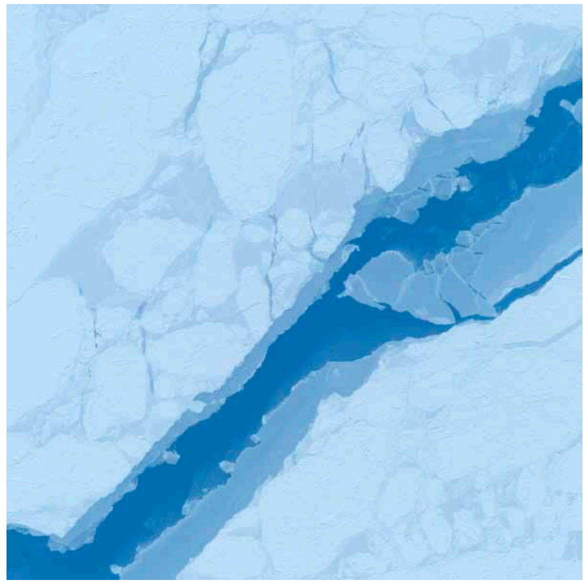

Figure 4. A *lead* in the sea ice, as viewed from the ER-2 digital camera system.

First light for MABEL came during a campaign out of Dryden in December 2010, and subsequent Dryden-based campaigns followed in March–April 2011 and February 2012. Goals of these early flights were to work out residual issues with MABEL operation and to collect science-quality data over vegetation targets in the Sierra Nevada mountain range, Mojave Desert, and Colorado; over salt flats in Utah and New Mexico; over the densely populated urban centers in the Los Angeles basin; and over Lake Mead, the Great Salt Lake, and the Pacific Ocean.

MABEL to the Arctic

In an effort to collect data more appropriate for ice-sheet and sea-ice algorithm development, a substantially larger Arctic campaign took place in April 2012. Based out of Keflavik, Iceland, MABEL was used for surveys over Greenland, the Arctic Ocean, Svalbard, Norway, and Iceland.

Over the course of the Arctic campaign, other instruments were flown concurrently to aid ICESat-2 researchers interpreting MABEL data. The Cloud Physics Lidar (CPL), a mature instrument that has used routinely since 2000, provided algorithm developers with a sense of the atmospheric conditions and cloud-cover surveyed simultaneously by MABEL. To provide sea-ice algorithm developers with a sense of the size and distribution of stretches of open water within the sea ice called *leads*—see **Figure 4**—a digital camera system, with 1-m (~3.3-ft) spatial resolution, was also flown concurrently with MABEL—see **Figure 5**.

Figure 5. [*Top*] Image taken by NASA pilot **Tim Williams**, at 20-km (~12-mi) altitude. [*Bottom*] A sample image from MABEL's digital camera system. Three icebergs in each image are labeled to provide reference; iceberg 'A' is approximately 1 km (~0.6 mi) across.

Two MABEL flights were flown simultaneously with another NASA mission working in the Arctic—*Operation IceBridge*[3]. The laser altimeters associated with Operation IceBridge—the Airborne Topographic Mapper (ATM) and the Land, Vegetation, and Ice Sensor (LVIS)—are more mature than MABEL, providing ICESat-2 researchers with an external means of validating their ground-finding algorithms. Additionally, the Operation IceBridge camera system—referred to as the Digital Mapping System

[3] NASA's Operation IceBridge images Earth's polar ice in unprecedented detail to better understand processes that connect the polar regions with the global climate system, and serves as a "data bridge" between ICESat and ICESat-2.

(DMS)—is highly sophisticated, with a nominal 10-cm (~3.9-in) spatial resolution and more-precise image geolocation than that of the camera flown on the MABEL ER-2. The coordination of the MABEL and Operation IceBridge flights was so precise with respect to both space and time that the digital camera system flown on the ER-2 captured the Operation IceBridge P-3 aircraft and its shadow—see **Figure 6.**

Figure 6. Operation IceBridge P-3 *Orion* aircraft (and its shadow), flying at approximately 450 m (~1476 ft) over the Greenland Ice Sheet, captured in an ER-2 digital camera system image, flying at approximately 20 km (~12 mi).

Further validation of MABEL data involved coordination with collaborators who were already in the field—on the ice sheet itself. These collaborators offered various kinds of MABEL support, including providing field photos and descriptions of the ice-sheet surface; conducting a 6-km (~3.7-mi) GPS traverse of a MABEL data line; and installing precisely located corner-cube reflectors, whose signatures proved to be visible in the MABEL data.

The Arctic deployment received necessary and eminently useful weather forecasting support from the Icelandic Meteorological Office (*en.vedur.is*), and experienced very favorable conditions for an airborne laser altimetry campaign. Therefore, MABEL was able to successfully complete 12 missions based out of Keflavik, for a total of nearly 80 flight hours, or more than 50,000 km (~31,069 mi) of science flight lines, and approximately 5 terabytes of data. **Figure 7** (next page) is a map associated with the Arctic campaign that offers a sense of the distribution of these flight lines. The map also indicates sections of the survey where validation data were provided by other airborne or field-based collaborators.

The next set of MABEL flights was based out of NASA's Wallops Flight Facility in September 2012 and focused on targets of interest to the ecosystem-science community. These data will be a key component in developing algorithms to recover tree canopy height (used as an input to biomass estimates) from the ICESat-2 mission.

Summary

ICESat-2, slated for launch in 2016, will continue the important observations of ice-sheet elevation change, sea-ice freeboard, and vegetation canopy height begun by ICESat in 2003. Together, these datasets will allow for continent-wide estimates in the change in volume of the Greenland and Antarctic ice sheets over a 15-year period, and long-term trend analysis of sea-ice thickness.

Our airborne ICESat-2 simulator—MABEL—has proven to be an excellent platform to help the research community prepare for the unique challenges and opportunities the ICESat-2 data will provide. MABEL data have proven useful for both science algorithm development and in processing and handling the large data-rate that these types of systems generate, and has been invaluable in helping the team to prepare for handling ICESat-2 data. The team expects to conduct additional MABEL campaigns in the coming months and years, to generate further test data needed to prepare for the launch of ICESat-2.

For more information about ICESat and ICESat-2, visit: *icesat.gsfc.nasa.gov/icesat2/index.php.* ■

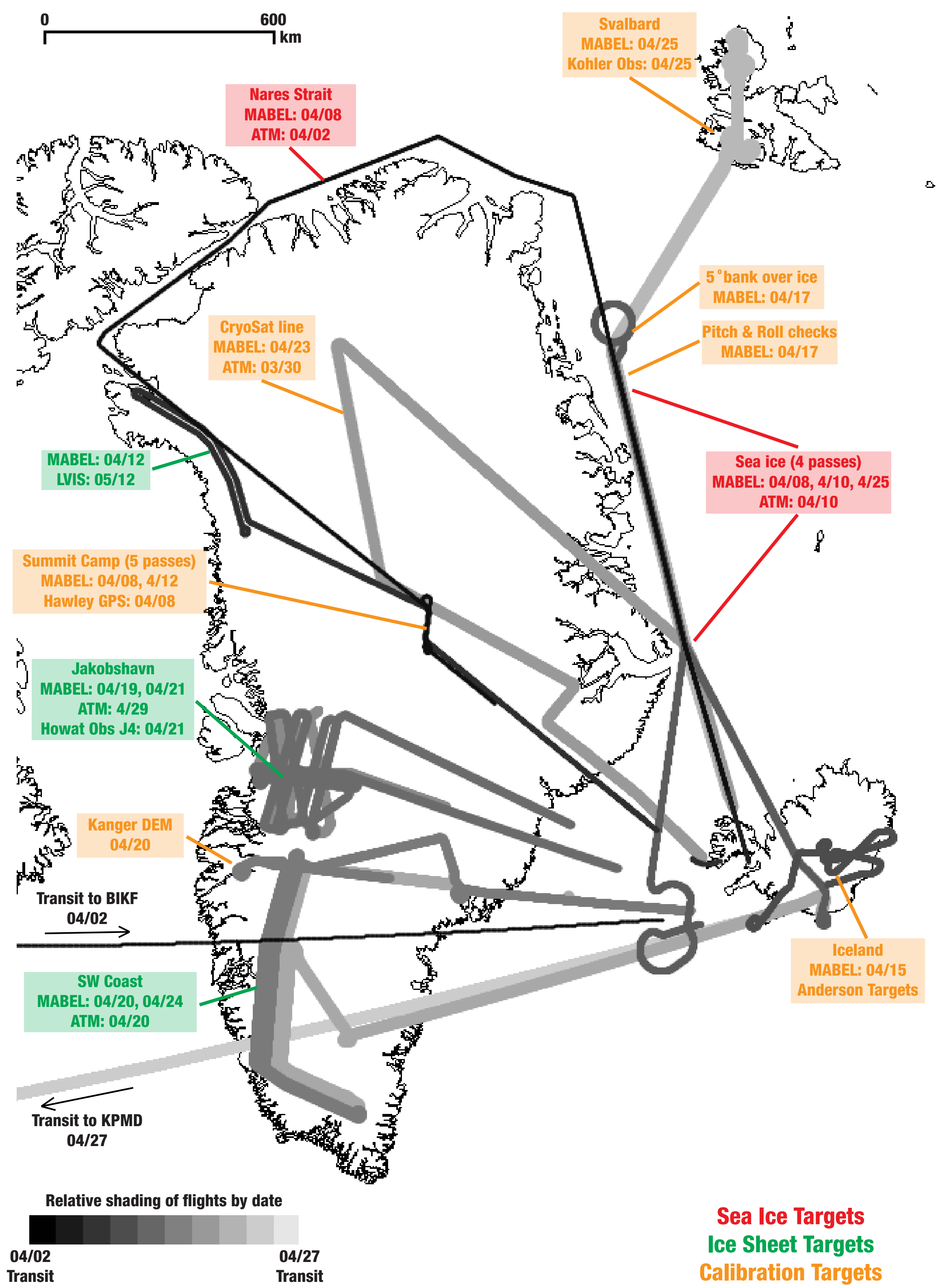

Figure 7. *Map of the April 2012 MABEL Arctic campaign.* MABEL flew 12 missions based out of Keflavik, Iceland, for a total of nearly 80 flight hours, resulting in more than 50,000 km (~31,069 mi) of science flight lines.